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Final Report

on

TYPE 321 (18-8+Ti) STAINLESS STEEL TUBING IN THE REHEATER OF NUMBER 2 STEAM GENERATOR AT THE RIVER ROUGE STATION OF THE DETROIT EDISON COMPANY

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REPORT
ON
TYPE 321 (18-8+Ti) STAINLESS STEEL TUBING IN THE REHEATER OF NUMBER 2 STEAM GENERATOR AT THE RIVER ROUGE STATION OF THE DETROIT EDISON COMPANY

Creep-rupture failures occurred prematurely in March 1960 and March 1961 in the Type 321 (18-8+Ti) stainless steel tubing in the reheater of Number 2 Steam Generator at the River Rouge Station of The Detroit Edison Company. The service times when failure occurred were approximately 16,000 and 22,000 hours. The investigations of these failures by The Detroit Edison Company had shown the following:

(1) Overheating of individual tubes had occurred as a result of uneven steam flow.

(2) Tubes which had not failed exhibited marked evidence of residual cold work from the cold reduction during manufacture.

(3) The two failed tubes exhibited no cold work but had an extremely fine grain size.

(4) The design operating conditions of 1100°F metal temperature and 6000 psi stress were so mild that even the weakest known condition of Type 321 steel should have been adequate for the expected service life of the reheater.

The discovery that tubes with considerable cold work were in the superheater raised a serious question as to the suitability of the tubes for the service. Standard practice requires that the tubes be annealed to cause at least complete recrystallization. Very little information is available regarding the creep-rupture properties of cold-worked Type 321 alloy. The reheater was placed in service during the period when the low creep-rupture strength of fine-grained Type 321 tubes was determined to be a cause of premature failures in superheater tubes. In view of the low service stress at 1100°F, it had been judged, however, that the reheater tubing would be adequate even though it was fine grained. It was not known then that at least part of the tubing was cold worked.

The overheating was corrected by controlling the steam flow. However, in view of the uncertainties of the properties of the tubing remaining in the reheater, an investigation was undertaken to answer the following two questions:

(1) What is the expected future life of the tubing?

(2) What benefits would be derived from heat treating the remaining tubing?

Answers to these questions were obtained by conducting creep-rupture tests on samples of tubing from the reheater. The results of tests at the University were supplemented by tests carried out by The Detroit Edison Company. A limited amount of metallographic examination work was done to obtain structural information on the test materials to correlate with the test results.

The experience gained at the University under Project SP-6 was used in the investigation. This project carried out an extensive investigation of Type 321 superheater tubing. It was carried out with the financial assistance of the EEI under the direction of the Steam Power Panel of the ASTM-ASME Joint Committee on the Effect of Temperature on Properties of Metals.

CONCLUSIONS

The creep-rupture strengths of the tubes varied from extremely weak to normal strength expected for good Type 321 tubing. The weakest tube was the extremely fine-grained Tube Number 13 which had failed. The tubes with residual cold work gave intermediate to high strength. Future premature failures would be dependent on whether or not there are tubes present as weak as Number 13. Consideration of the probable creep characteristics of tubes such as Number 13 indicates that continued checking of tube diameters at the interval of about one year would detect swelling and allow replacement prior to failure. The absence of swelling at the present time indicates that either such weak tubes are not present or the service temperature is now below 1100°F.

Heat treatment of the tubes at 2050°F would provide expected levels of strength for the alloy and would eliminate all question as to future serviceability due to presence of extremely weak tubes. It is, therefore, a matter of relative costs as to whether the tubes should be continued in service with checks for swelling and replacement of swelled tubes, if they should occur, versus the cost of heat treatment. In view of the known information, it is recommended that the tubes be continued in service without heat treatment.

Service History of Reheater

Two failures of tubes had occurred in the reheater. The first occurred in March 1960 when the service time was about 16,000 hours and the second in March 1961 when the service time was about 24,000 hours. Operating conditions were expected to be approximately 1100°F metal temperature at a stress of 6000 psi. It was known that during early operation of the reheater, considerably higher temperatures than 1100°F occurred on some tubes due to uneven steam flow. The uneven steam flow and excessive metal temperatures were reported to have been corrected since the second failure.

At the time of the second tube failure, a program of checking the diameter of tubes in the reheater for excessive creep was instituted. Checks in June and September of 1961 gave no indication of swelling by creep.

It was known that tubes in the reheater had been made from heats from more than one producer.

Description of Tubes Tested

Samples of three tubes were submitted for creep-rupture tests. Tubes Number 3 and 18 were removed at the time of the failure in 1961. Neither had exhibited measurable swelling by creep. The Detroit Edison Company also conducted tests on Tube Number 12 which was similar to Tubes Number 3 and 18. All were intended to be representative of the tubing which remains in the reheater.

Tube Number 13 was a section adjacent to the fracture in the tube which failed in March 1961. It was included in the program as an example of failed tubing and because it had a different microstructure than the other tubes. Also, a small piece of the tube which failed in March 1960 had been submitted to the University under the SP-6 research program and had been examined for microstructure.

The Detroit Edison Company analyzed the tubes for chemical composition with the following reported results:

Tube Number	C	Mn	Si	Cr	Ni	Ti	Mo
3	0.075	1.2	.51	18.3	12.0	.39	.19
12	0.079	1.2	.53	18.7	11.6	.40	.17
18	0.083	1.4	.55	18.3	11.0	.41	.19
13	0.079	1.1	.73	20.2	11.0	.47	<0.10

The tubes were 2.5-inch O.D. by 0.135-inch wall thickness.

The number of the tubes identified the platten from which they were removed. Part of the specimens tested were further coded as to location as follows:

M = Middle of 6 foot long section of tubing removed
B = Bottom of 6 foot long section of tubing removed
S = Side with respect to gas flow
F = Facing gas flow
B = Opposite gas flow

PROCEDURE

The specimens used for the tests were 22-inch long strips cut lengthwise from the tubing. A $2\frac{1}{4}$-inch long gage section, $\frac{1}{2}$-inch wide and the full thickness of the tubes, was machined at the center of the strips. Specimens were machined both by The Detroit Edison Company and by the University.

The testing program was designed as follows:

(1) Determine the properties of tubes remaining in the reheater.

Tubes Number 3, 12, and 18 were used for this purpose. Most of the rupture tests on Tubes Number 3 and 12 were conducted by The Detroit Edison Company. The University conducted one long time rupture test on Tube Number 3 as a check on the results obtained by The Detroit Edison Company. In addition, the University conducted a creep test on a specimen from Tube Number 3 at 1100°F and 6000 psi to obtain an indication of the present creep rate of the tubing in service.

(2) Determine the response of the tubing to a proper heat treatment with the objective of establishing the value of heat treating the tubing to improve future serviceability. Specimens from Tube Number 18 were used for this purpose. There was insufficient material remaining from Tubes Number 3 and 12 for tests of this type.

(3) Determine the properties of failed tubes.

Specimens from Tube Number 13 were used. The rupture strength of this tube proved to be so low that it was included in the program to determine the effect of heat treatment.

The heat treatment applied to Tubes 13 and 18 was ½ hour at 2050°F and water quenched in accordance with the usual heat treatment now applied to Type 321 superheater tubing.

The evaluation of existing properties was based on rupture tests at the expected operating temperature of 1100°F. Because the maximum times for rupture tests were limited to the order of 1000 to 2000 hours, a limited number of tests were conducted at 1200°F to help determine the reliability of extrapolation of the stress-rupture time curves at 1100°F. It was assumed that if the slope of the stress-rupture time curves at 1200°F was similar to those at 1100°F, the curves at 1100°F could be extrapolated with considerable confidence. Tests at 1200°F also gave data which could be compared with the data accumulated under the SP-6 project and the preponderance of the data in the literature.

The materials as-removed from service and the heat treated materials were examined metallographically to determine the structures of the test materials.

All rupture and creep tests were conducted in accordance with ASTM Recommended Practice E-139. The specimens were brought to temperature in four hours and the stress applied.

RESULTS

The rupture strengths derived from the tests are given in Table 1. The test data for Tubes Number 3 and 12 are given in Table 2, Tube Number 13 in Table 3, and Tube Number 18 in Table 4. The rupture strengths given in Table 1 were read from the stress-rupture time curves of Figure 1. The rupture properties show the following:

(1) A wide range in rupture strengths of the tubes as-removed from service with the specimens from the failed Tube Number 13 being very weak, Tubes 3 and 12 intermediate, and Tube Number 18

having nearly expected strengths for the alloy. Type 321 alloy when properly heat treated should have a stress for rupture in 100,000 hours at 1200°F of 9000 or 10,000 psi or higher. Only Tube Number 18 indicated strengths at this level. Tube Number 13 had the lowest rupture strengths known to the authors for Type 321 alloy.

(2) The slopes of the curves indicated by the tests at 1200°F were similar to those of the curves defined by the tests at 1100°F. This indicates that the curves at 1100°F would not show a decrease in slope if longer tests were conducted and, therefore, can be extrapolated with confidence. The only exception to this was Tube Number 13 where the slope at 1200°F was sufficiently greater than at 1100°F to raise a question as to whether indicated strengths from extrapolation at 1100°F might even be lower than shown by the extrapolation in Figure 1.

(3) The tests at 1200°F after reheat treatment at 2050°F, while very limited in extent, indicated that both Tubes Number 13 and 18 had the level of strength to be expected for the alloy when properly heat treated. This conclusion is based on the similarity of the data to a large amount of data collected under Project SP-6.

(4) Because the data for reheat treated specimens at 1200°F indicate normal rupture strength, it is certain that reheat treatment would develop expected properties at 1100°F for Type 321 alloy in the tubes. The fact that the stress-rupture time curve at 1200°F after reheat treatment of Tube Number 13 was at a higher level of stress than the curve at 1100°F for material as-removed from service is ample evidence to support this conclusion.

(5) Tube Number 18 had a high level of strength as-removed from service. Therefore, based on the SP-6 research, it was not expected that heat treatment would materially change strength. As expected, all the reheat treatment did was to remove the reduction in short time strength, which is characteristic of tubing removed from service.

The creep curve for the 6000 psi test at 1100°F on Tube Number 3 is shown in Figure 2. The creep rate at about 2000 hours was 0.034 percent per 1000 hours, a value consistent with the rupture strength. In theory, there should not have been the long period of decreasing creep rate in this test if the test conditions of 6000 psi at 1100°F had matched the service stress and temperature. Presumably, the main reason the prolonged decrease in creep rate occurred was due to the service conditions prior to removal being less severe. It is known, however, that when specimens are cut from a piece after prior creep that there is a period of readjustment during which creep rates decrease down to the actual levels in service. The test, therefore, demonstrates quite well what the creep rate is for tubes in the reheater at 1100°F with the strength level of Tube Number 3.

The structure of Tube Number 13 was initially very fine grained (Figure 3a) with a considerable amount of sigma phase as particles in the grain boundaries. The tube which failed in March 1960 (Figure 3b) had a similar structure and was possibly even finer grained. Tubes Number 3 and 18 had structures (Figures 4 and 5) consisting of mixtures of severely cold-worked coarse grains plus very fine grains derived from partial recrystallization. The recrystallization was more extensive in Tube Number 3 than 18.

Heat treating Tube Number 13 at 2050°F for ½ hour and water quenching coarsened the grains (Figure 6). It did not, however, result in complete solution of all carbides. The same heat treatment applied to Tube Number 18 caused complete recrystallization and grain growth (Figure 7). The grain size of Tube Number 18 was mixed and finer than Tube Number 13 after heat treatment.

Specimens were examined microscopically after testing without disclosing any features significant to the purposes of this investigation. No evidence was found to indicate that further recrystallization (Figure 5) had occurred in either Tube Number 3 or 18 during tests at 1100° or 1200°F.

The hardness of as-removed tubes was measured with the following results:

Tube Number 13 -- 181 Vickers Hardness Number
Tube Number 3 -- 210 Vickers Hardness Number
Tube Number 18 -- 223 Vickers Hardness Number

It is evident that Tubes Number 3 and 18 retained a substantially higher hardness than annealed material as a result of the cold work present. The high hardness of Tube Number 13 could be due to the exposure and creep during service. The expected hardness for complete recrystallization for heat treatment at 1600°F is about 160 VHN.

DISCUSSION OF RESULTS

The future performance of the tubing in the reheater is estimated from the test data as follows:

(1) All tubing in the reheater with creep-rupture strength similar to that of Tube Number 18 should give no difficulty. The operating stress of 6000 psi at 1100°F is only 37 percent of the 100,000 hour rupture strength of 16,000 psi. The ASME Boiler and Pressure Vessel Code allows a stress of 10,400 psi at 1100°F for material with this rupture strength.

(2) The operating stress of 6000 psi is 50 percent of the estimated 100,000 hour rupture strength of Tube Number 3 at 1100°F. Thus, on the basis of rupture strength, the strength of all tubes in the reheater down to that of Tube Number 3 should be adequate for the future of the reheater. The creep test on the specimen from Tube Number 3 at 6000 psi gave a creep rate of 0.034 percent per 1000 hours. The use of creep data for Type 321 steel is difficult. Very prolonged testing is usually required to develop true secondary creep in tests on the alloy. It usually exhibits a period of relatively rapid creep rate soon after the stress is applied to a new specimen. It was

expected, in this case, that the prior service would have eliminated this period and the test at 6000 psi should give near true minimum creep. It is thought that this had not occurred in service for unknown reasons and the test did not give true minimum creep. On the other hand, if it did, the creep test indicates that difficulty due to excessive creep should not start to occur in tubes as weak as Tube Number 3 in 60,000 to 100,000 hours with a metal temperature of 1100°F.

(3) If tubes with creep-rupture strengths ranging down from Tube Number 3 to that of Tube Number 13 still remain in the reheater, trouble from excessive creep could be expected for metal temperatures of 1100°F at 6000 psi in considerably less time than 60,000 hours. Material with the strength of Tube Number 13 would be expected to have a minimum creep rate of no less than, and probably more than, 0.1 percent per 1000 hours at 6000 psi. Material of this type thus should show noticeable creep in 10,000 to 20,000 hours and excessive swelling in not too much longer time. The fact that the measurements to date of diameters of tubes in the reheater have not shown creep of this order of magnitude indicates that there are no tubes creeping this fast. This could be due to the absence of any tubes as weak as Tube Number 13 or to the actual temperatures of such tubes being below 1100°F.

In view of the measurements to date indicating that no tubes are creeping at an excessive rate, it is recommended that the tubes be continued in service. If it is certain that the control of steam flow will limit the temperature of any tube to no more than 1100°F, even the weakest possible tubing should not accumulate creep at more than about 1 percent in 10,000 hours. This indicates that if the tube diameters were measured on a yearly basis, it should be possible to locate such weak tubes by diameter measurements well in advance of actual failure.

Heat treatment at 2050°F of the tubes in the reheater would bring the creep-rupture strengths up to expected levels for the alloy. They should then have far more strength than would be required for the service. The creep-rupture ductility was less after the heat treatment than is characteristic of new tubing. Most all tubes from service have such low ductility when heat treated. It is assumed, however, that the ductility would be adequate for the service. The tubes in many superheaters have been reheat treated with successful subsequent service.

The choice of retaining the tubes in service in their present state or heat treating to insure a high level of strength, therefore, reduces to a matter of economics.

There is one additional reason to suggest that there may be no tubes present as weak as the data indicated for Tube Number 13. This tube had failed by creep. Material adjacent to the failure may have exhausted a large percentage of its creep-rupture life before the tests were made. If that were the case, the strengths would be expected to be exceptionally low. The tube measurements demonstrated that none of the remaining tubes had undergone excessive creep. If prior creep was the cause of low strength in the specimens from Tube Number 13, there should, therefore, be no tubes as weak in the reheater.

The conclusions of this investigation would be considerably strengthened if the cause of the observed microstructures were understood. The possibilities to account for the various microstructures and the strength levels have been considered at some length. The most likely explanations are as follows:

(1) The tubes are known to have been produced by more than one manufacturer. It could be assumed that one group of tubes was completely recrystallized at a very low temperature, such as 1600°F, to a very fine grain size. The first tube which failed and Tube Number 13 would be this type. Due to overheating from uneven steam flow, these tubes were exposed to temperatures in excess of

1200°F and underwent rapid creep as would be expected from their grain size at this temperature. When tested after failure, a substantial amount of the creep-rupture life of Tube Number 13 had been used up. Consequently, very low strength was indicated by the tests.

(2) Other tubes from another manufacturer could have been only partially recrystallized during heat treatment. The strength level of these tubes remained relatively high but variable. This would account for the strength of Tube Numbers 18, 3, and 12. The authors do not know of data for such partially-recrystallized structures. Tube Number 3 was recrystallized more than Tube Number 18 and had lower strength. It could be that the strength decreased with degree of low temperature recrystallization.

The possibility that fully cold worked tubes were installed does remain. It seems unlikely, however, because it is difficult to understand how such tubing could have been successfully installed in the reheater. Furthermore, it seems unlikely that heat treatment could have been inadvertently omitted by more than one manufacturer. It is known, however, that recrystallization would occur during service in such tubing. It is not possible, however, to account for the high strength of Tube Number 18 if it had been installed fully cold worked. The SP-6 research indicates that even a heat with a high level of strength would have had only half the strength of that tube. Complete recrystallization during service, however, would have been expected to lead to extremely low strength, such as was found for Tube Number 13 and still must be considered a possibility. The chances are, however, that fully cold worked tubing was not installed.

Table 1

Rupture Strengths at 1100° and 1200°F for Tubes from the Reheater, Number 2 Steam Generator, River Rouge Power Plant

Tube No.	Temp (°F)	Condition	Stress for Rupture in Indicated Time Periods (psi) 100-hour	1000-hour	10,000-hour	100,000-hour
13	1100	As-Removed	27,000	17,000	11,000	(7,000)
3	1100	As-Removed	35,000	25,500	17,500	12,000
12	1100	As-Removed	35,000	25,500	(17,500)	--
18	1100	As-Removed	39,000	29,000	22,000	6,000
13	1200	As-Removed	19,000	10,000	(5,700)	(3,200)
12	1200	As-Removed	25,000	16,000	(11,000)	(7,000)
18	1200	As-Removed	28,000	20,000	(14,000)	(10,000)
13	1200	W.Q. 2050°F	31,000	21,000	(14,500)	(10,000)
18	1200	W.Q. 2050°F	34,000	22,500	(15,000)	(10,000)

Values in (___) obtained by excessive extrapolation

Table 2

Stress-Rupture Time Data for Tubes Number 3 and 12 As-Removed from Service

Tube No.	Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 inches)	Testing Laboratory
3MS	1100	35,000	101	34	DE
3MF	1100	28,000	874	31	DE
3MB	1100	25,000	998	46	DE
3BS	1100	22,000	3171.1	27	UM
12MS	1100	35,000	130	30	DE
12MF	1100	28,000	809	34	DE
12MB	1100	25,000	1233	45	DE
3MS	1200	22,000	229	36	DE
12TS	1200	24,000	124	43	DE
12MS	1200	22,000	201	30	DE
12TS	1200	18,500	496	34	DE

Table 3

Stress-Rupture Test Data for Tube Number 13 (Tube which Failed in Service During March 1961)

Condition	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 inches)	Testing Laboratory
As-Removed	1100	28,000	80	52	DE
As-Removed	1100	22,000	293.1	66	UM
As-Removed	1100	17,000	1087.1	64	UM
As-Removed	1200	17,000	138	75	UM
As-Removed	1200	14,000	291.7	68	UM
½ hr. 2050°F, W.Q.	1200	30,000	123.6	6.2	UM
½ hr. 2050°F, W.Q.	1200	23,000	613.3	12	UM

Table 4

Stress-Rupture Data for Tube Number 18
(All tests conducted at the University of Michigan)

Specimen	Condition	Test Temp (°F)	Stress (psi)	Rupture Time (hours)	Elongation (% in 2 inches)
18MS	As-Removed	1100	35,000	253.8	17
18MS	As-Removed	1100	25,000	3506.9	21
18MB	As-Removed	1200	25,000	234.5	23
18MF	As-Removed	1200	20,000	1057	26
--	½ hr. 2050°F, W.Q.	1200	30,000	199.3	9
--	½ hr. 2050°F, W.Q.	1200	25,000	543.5	13

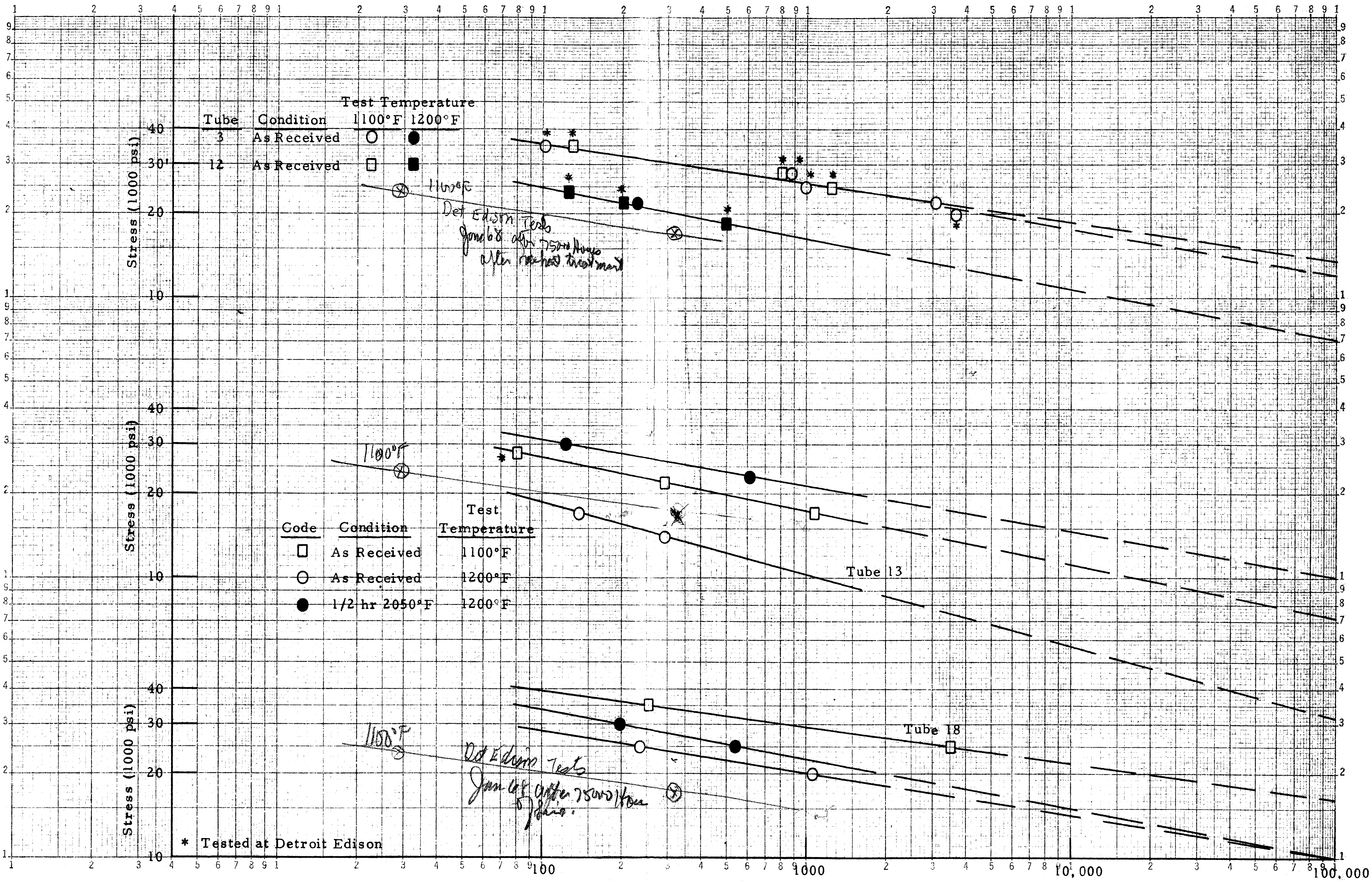


Figure 1 Stress-Rupture Time Curves for Type 321 Tubing from the Reheater. Number 2 Steam Generator River Rouge Power Plant.

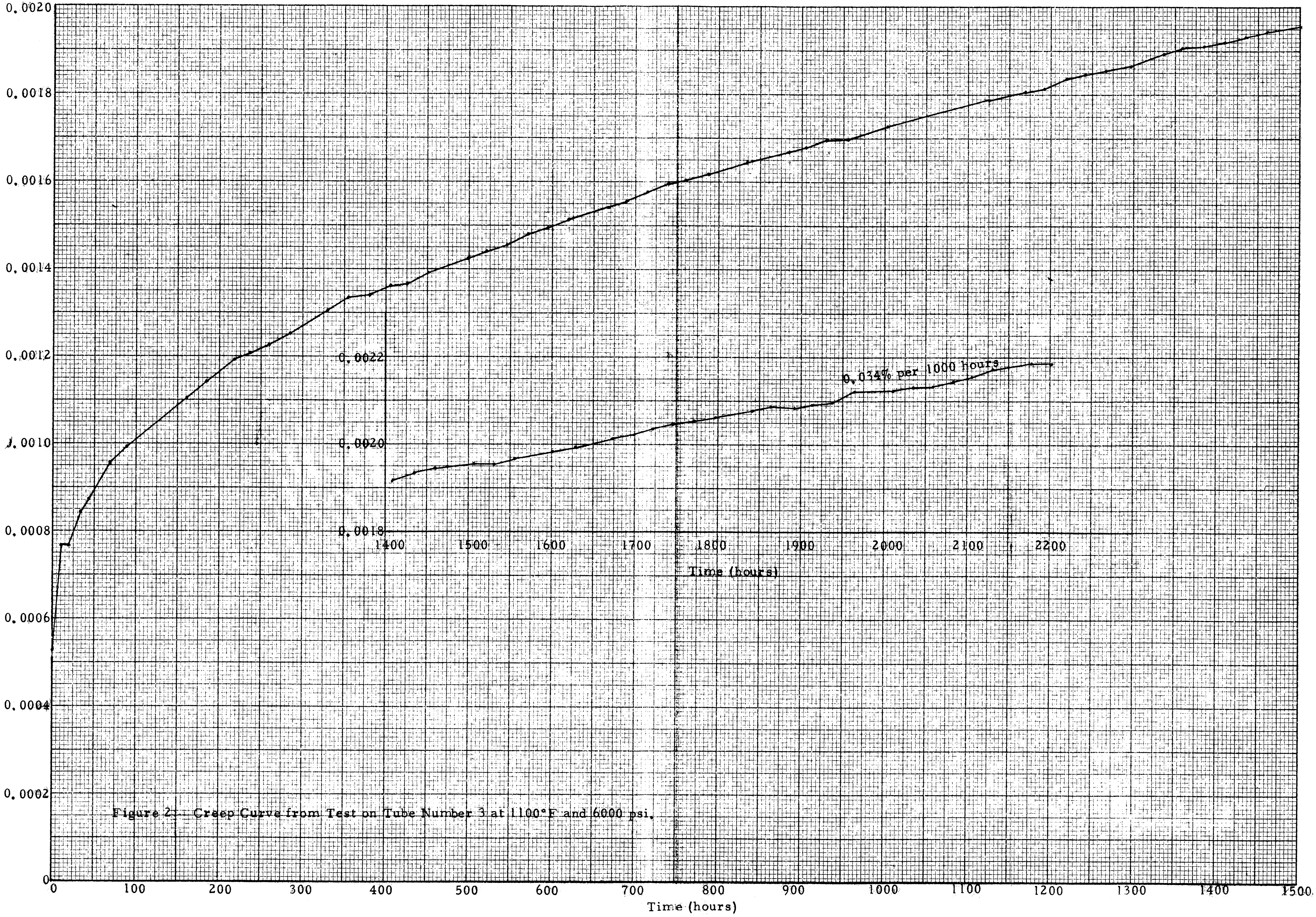
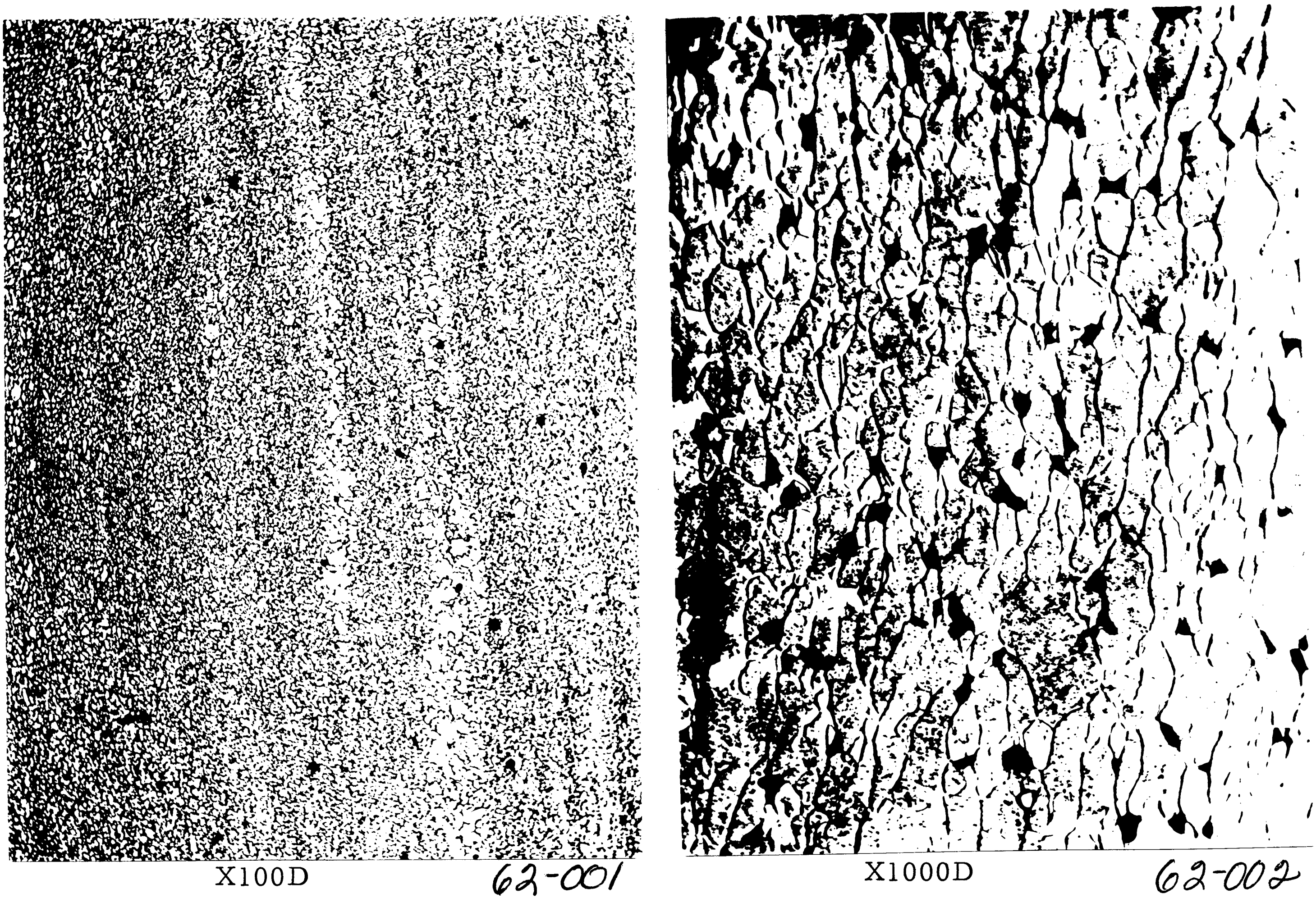
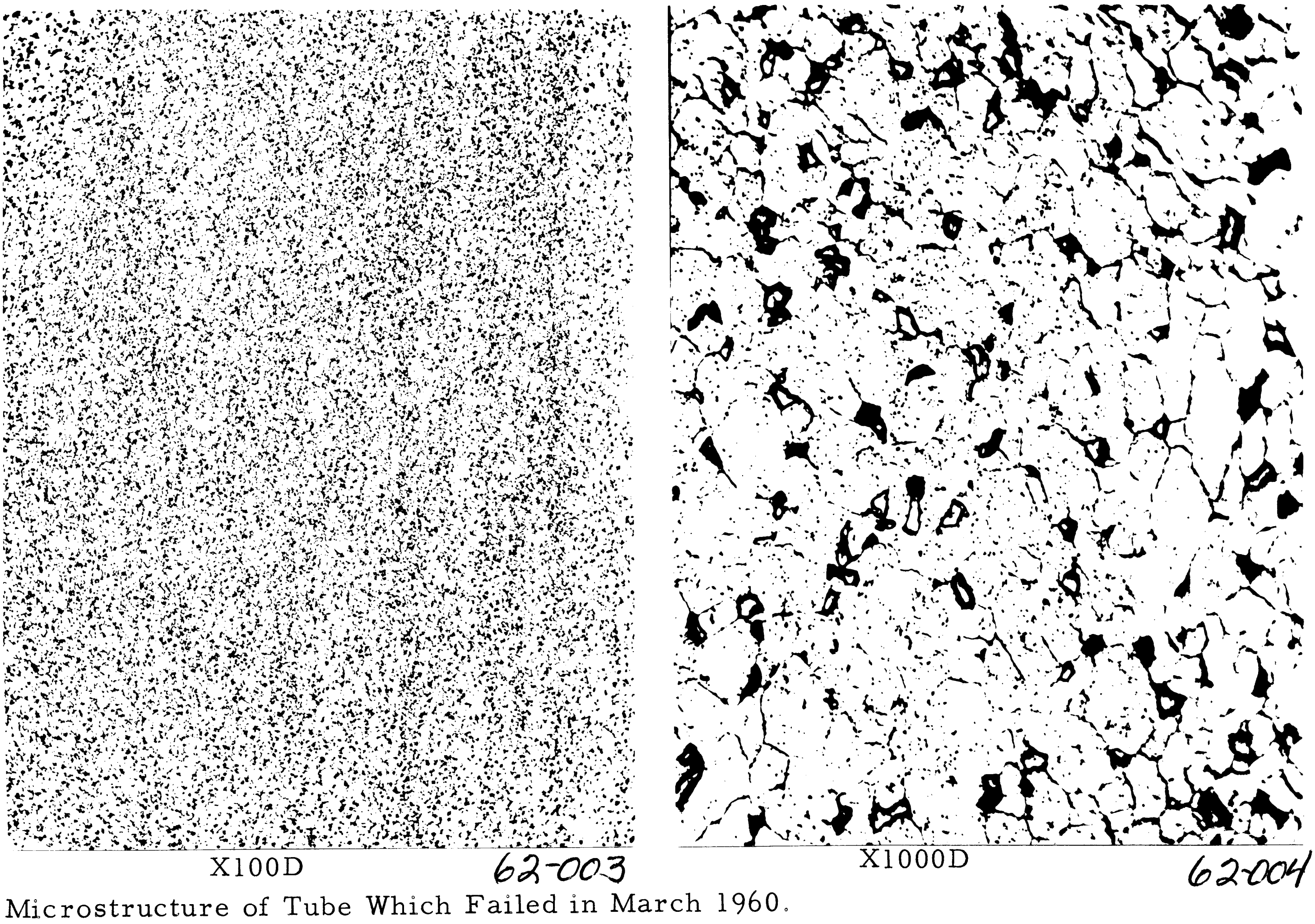


Figure 2: Creep Curve from Test on Tube Number 3 at 1100°F and 6000 psi.

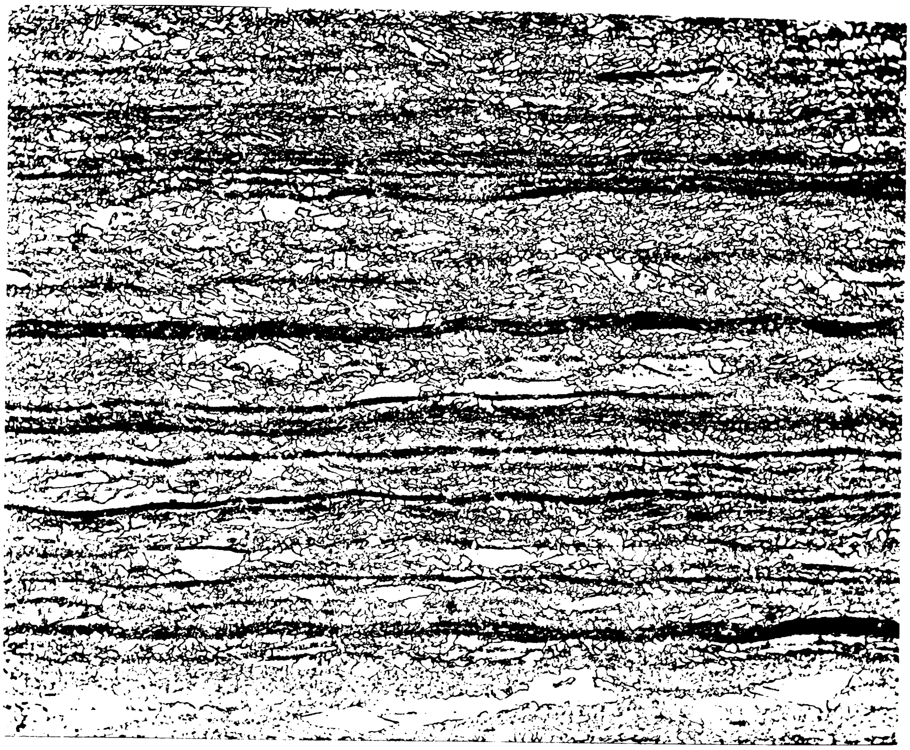


(a) Tube Number 13 As-Removed from Service After Failure in March 1961.

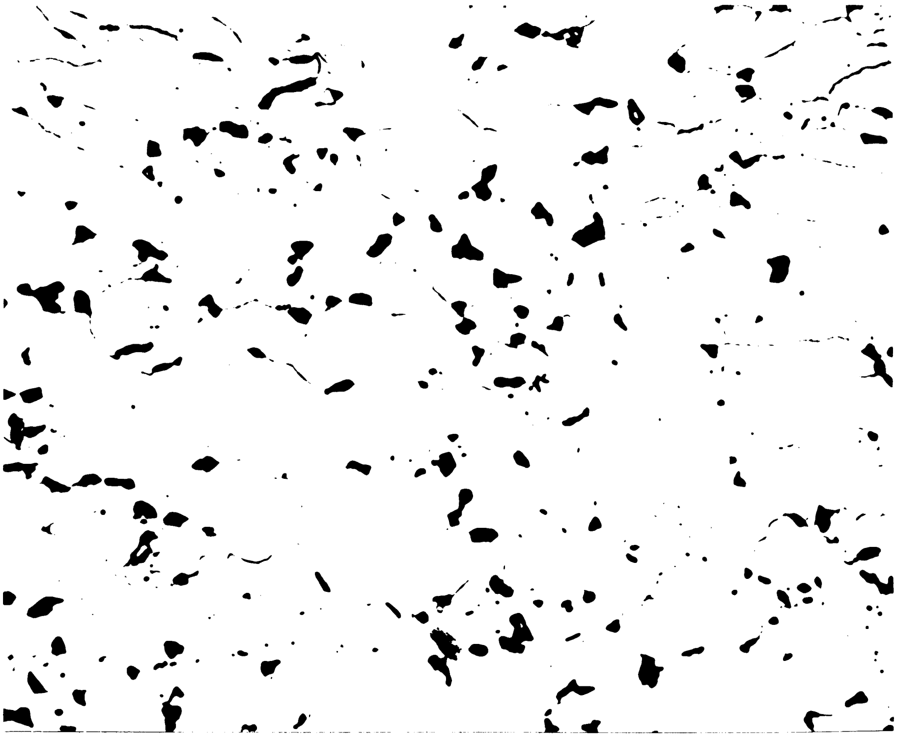


(b) Microstructure of Tube Which Failed in March 1960.

Figure 3 Microstructure of Failed Tubes.

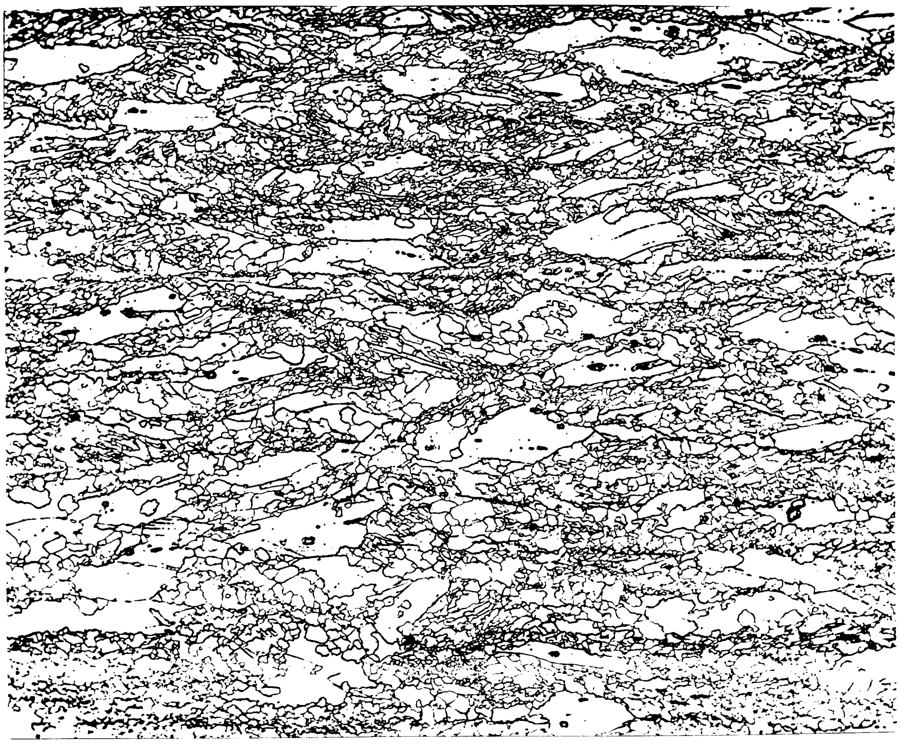


X100D 62-005



X1000D 62-006

Figure 4 Microstructure of Tube Number 3 As-Removed from Service.

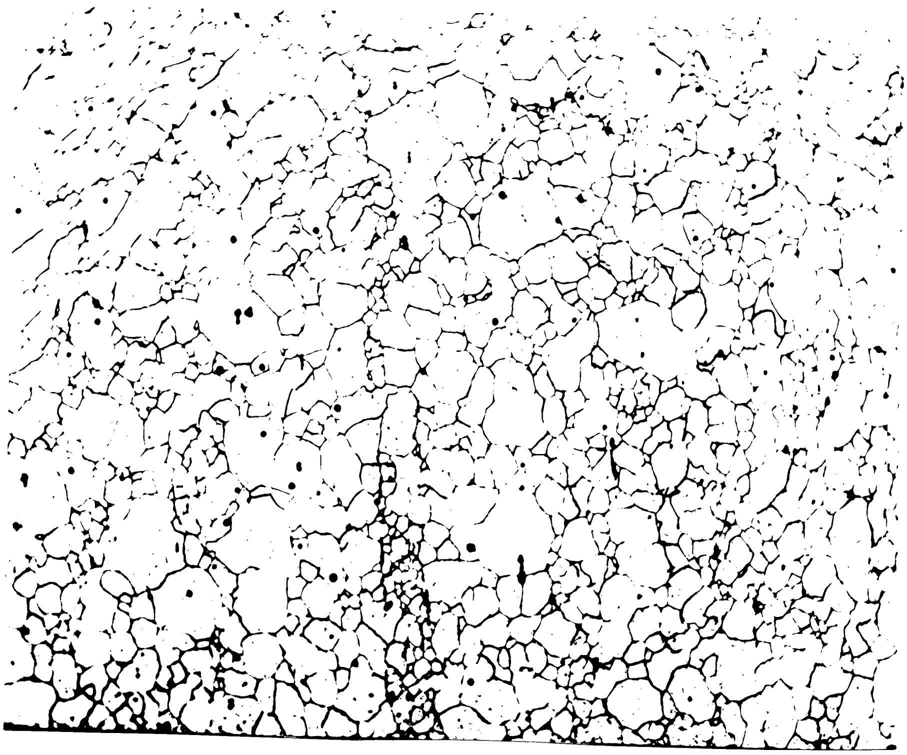


(a) As-Removed from Service - X100D 62-007

62-008

(b) As-Removed from Service Plus 1057 Hours at 1200°F Under 20,000 psi - X100D

Figure 5 Microstructure of Tube Number 18.



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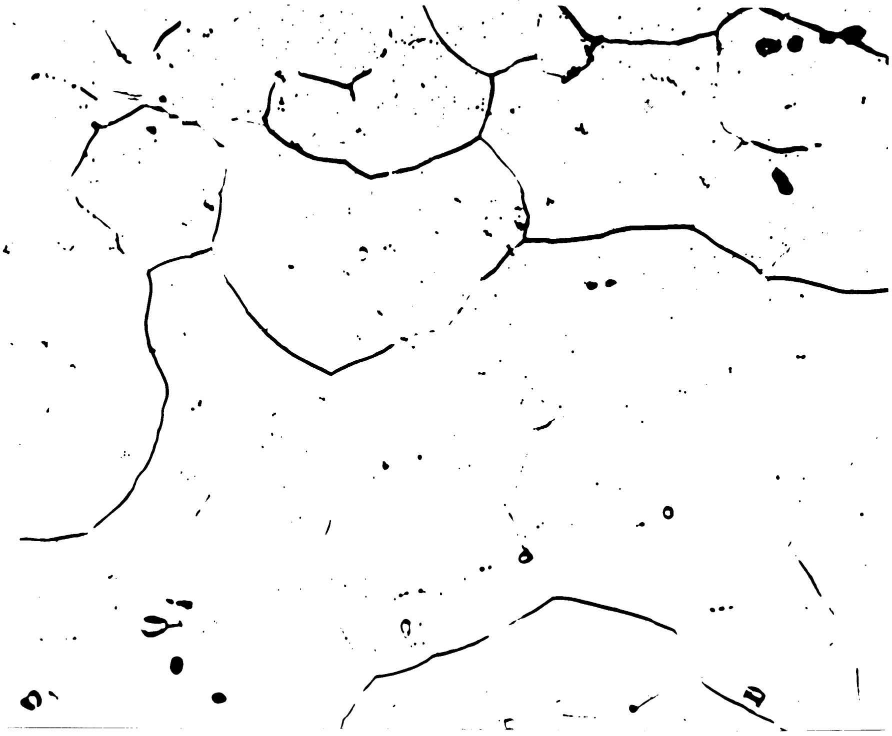
62-009



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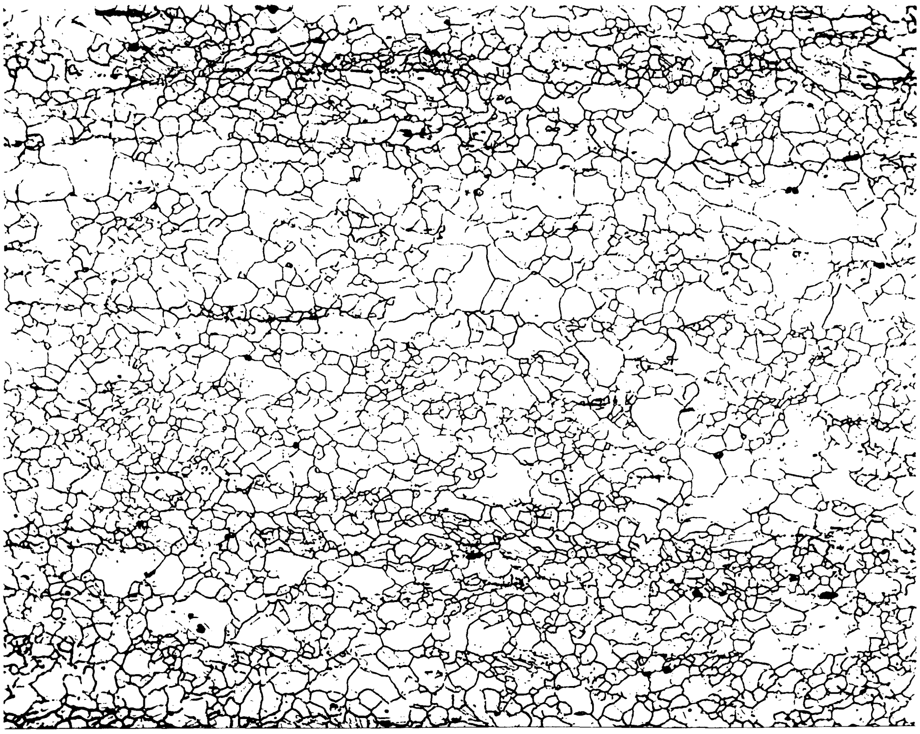
62-010

Figure 6 Microstructure of Tube Number 13 After Heat Treatment at 2050°F for One-Half Hour and Water Quenching.



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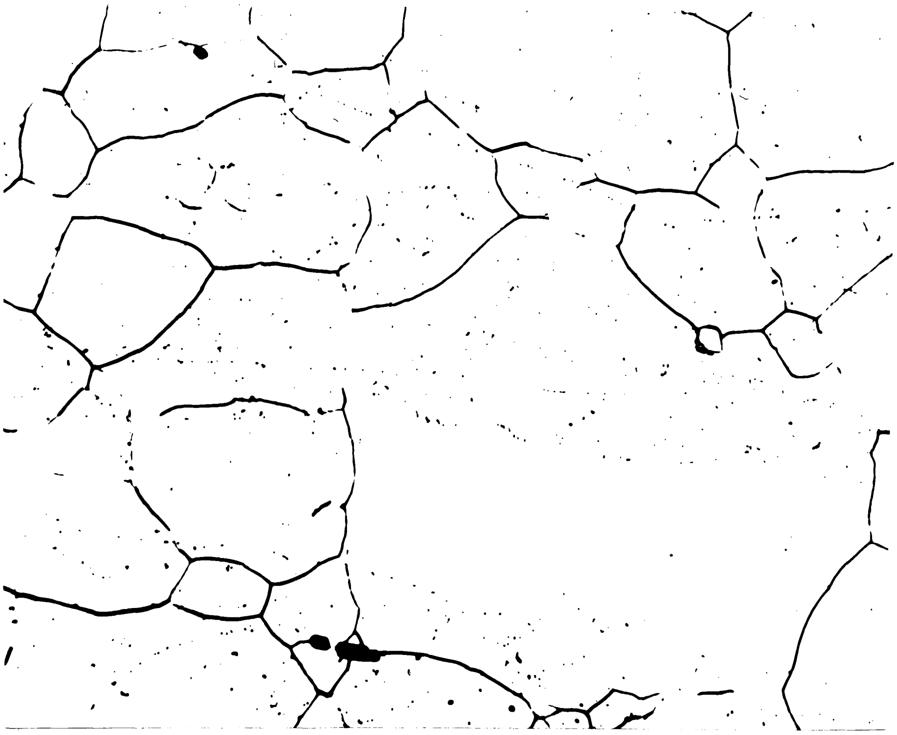

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Figure 7 Microstructure of Tube Number 18 After Heat Treatment at 2050°F for One-Half Hour and Water Quenching.